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DESIGN OF A COMBINED TUBE FEEDING AND CUTTING MECHANISM USING DESIGN FOR SIX SIGMA APPROACH

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ABSTRACT

Design for Six Sigma (DFSS) is a proactive approach that aims at designing in quality during the early stages of product or process development. In this paper, the DMADV (Define-Measure-Analyze-Design-Verify) methodology has been applied to an industrial process. The considered application involves cutting tubes to predefined lengths in order to be supplied to custom-made automotive exhaust tube manufacturers. Investigating the process reveals several problems that adversely affect the production. Accordingly, customer requirements have been identified and the Quality Function Deployment (QFD) has been implemented to translate these requirements into technical characteristics. A conceptual design of a compound mechanism for both feeding and cutting has been suggested to overcome the drawbacks in the current practice. A detailed 3D CAD model has been developed, in addition to a prototype that has been manufactured to test the validity of the proposed design. Pilot runs of the prototype reveal that the developed mechanism not only performs its intended task adequately, but also the chances of cutting wrong tube lengths have been eliminated.

KEY WORDS

Design for Six Sigma, Quality Function Deployment, Mechanisms, Cams

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INTRODUCTION

Design for Six Sigma (DFSS) is a systematic well-structured approach that integrates several tools to proactively build quality into products and services. The need for DFSS implementation has been motivated by the fact that, a high percentage of the total life cycle cost of a product is incurred during the early design phases. In addition, the cost of making design modifications or fixing design problems increases drastically through the product life cycle. Accordingly, DFSS is considered a cost-effective and powerful approach to product and process development as it incorporates the voice of the customer at the early stages of design. Besides, it establishes design quality through the application of preventive philosophies and tools supporting doing the right things at the first time during product development [1, 2].

The application of DFSS is not limited to the development of completely innovative new products or processes, but also it can be applied to redesign existing processes that are not capable of satisfactorily achieving the business objectives. DFSS implementation on existing processes is mostly accompanied by radical changes in the process, as opposed to the six sigma initiatives targeting to incremental continuous improvement. In some situation, DFSS may discard the existing practice and reengineer the process [3]. Reviewing the literature concerned with DFSS reveals that there are several methodologies that could be applied to design/redesign products or services. These methodologies include, but not limited to, the DMADV (Define-Measure-Analyze-Design-Verify) methodology, the IDDOV (Identify-Define-Design-Optimize-Verify) methodology, the IDOV (Identify-Design-Optimize-Verify) methodology, the DMADOV (Define-Measure-Analyze-Design-Optimize-Verify) methodology [4, 5]. The diversity of DFSS methodologies indicates that the approach is modular and it can be customized to fit different scenarios as stated by Gregory and Camille [6]. Nevertheless, DFSS mainly is not gaining its effectiveness from the methodology it adopts, rather the various tools incorporated in each stage of the methodologies are the dominant factor for successful implementation [7].

Despite the wide applicability of the DFSS methodologies in the literature, most of the studies apply these methodologies to design only products or service processes. However, their application in machines design/redesign is very limited. For instance, Hassan et. al. [8] applied the DMADV methodology for the sake of designing a portable water filter that is based on using a membrane filtration system. Meanwhile, design of a silicon micro-channel heat sink has been proposed by Jiang et. al. [9] as the result of the DMADV implementation. Moreover, Deshpande [10] attained significant design modifications for a food package via the DMADV methodology. Furthermore, El-Sharkawy et. al. [11] optimized the design of automotive heat exchangers using DFSS. Also, the design of exhaust manifold at Ford motor company using DFSS has been conducted by Gerhorst et. al. [12]. In the field of aerospace applications, the use of DFSS has been reported by several authors [13-15]. However, its application in designing manufacturing processes such as assembly, induction hardening, and grinding has been highlighted by Kalamdani and Khalaf [16]. For managing and improving the supply chain performance, the DFSS approach has been implemented to monitor and control the supply chain variables [17], as well as improve the information sharing in marine transportation [18]. In addition, several case studies including products as well as services that apply the IDDOV methodology have been presented by Cudney and Furterer [2], such as walker, military tool holder, hazardous chemical clean up system, solar heated jacket, and women's center for health services. Also, the DFSS has been employed to design the vaccination process in the healthcare field [19]. The DMADV methodology has been implemented by Mandahawi et. al. [20] to reduce the waiting time in an emergency department. Besides, significant reductions in patient waiting time and total cycle time have been achieved through using the DFSS in redesigning the health evaluation process [21].

This paper is mainly concerned with applying the DFSS approach to an industrial case study. The considered application involves cutting tubes to predefined lengths to be provided to custom-made automotive exhaust tube manufacturers. The DMADV methodology has been adopted and a different design for the tube cutting machine has been recommended to overcome the drawbacks in the current practice. The proposed design is based on a compound mechanism for both feeding and cutting of the tube. The developed tube cutting machine consists of slider-crank mechanism and cam mechanism, in addition to mechanical control parts such as; ratchet sprockets, cam follower and guides. The predefined lengths of tubes can be adjusted by selecting the different accurate strokes of crank-rocker mechanism. Moreover, cam mechanism affords an accurate control of the cutting process. The remainder of this paper is organized as follows: the subsequent section explains the details of the DMADV methodology, and then it is followed by the practical application of the considered case study. This section illustrates all the steps conducted in this research starting from the problem identification till the testing of the developed prototype. Then the paper ends with the conclusions.

RESEARCH METHODOLOGY

Among the various DFSS methodologies, this paper adopted the application of the DMADV methodology to an industrial case study. The implementation of this methodology entails following a path of five phases (Define, Measure, Analyze, Design, and Verify) in order to achieve customer satisfaction as shown in Fig. 1. The DMADV methodology is one of the most commonly applied DFSS methodologies in the literature. It has been reported by Larry and Tushar [4] that the DMADV can be established for various applications including process, service, and product design. Its wide applicability is due to the fact that the first three phases are shared with the DMAIC (Define-Measure-Analyze-Improve-Control) methodology. Although the same roadmap is followed by the two methodologies during the early phases of implementation, different tools should be incorporated to fit the targets for each methodology. The DMAIC approach focuses on improving existing processes, as opposed to the DFSS approach that is capable of achieving evolutionary improvements by discarding the existing processes and replacing them with new ones [3].

The different phases of the DMADV methodology have been thoroughly explained by several authors [2, 8, 15] . The first phase is the define phase, in which the DFSS project charter is created. In this stage, the problem statement in addition to the project objectives should be clearly identified. Responsibilities of the project team should be assigned and a plan for the project should be developed. Also, risks and opportunities should be assessed. The second phase is the measure phase that is concerned with conducting surveys to identify customer requirements as well as benchmarking competitors. Then, the critical to quality characteristics for the case

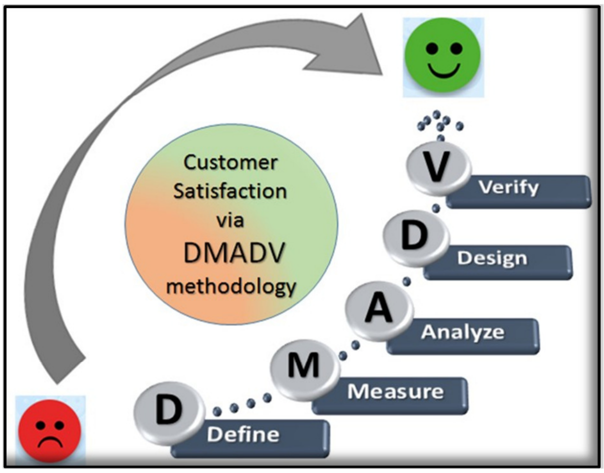


Fig. 1. DMADV methodology to achieve customer satisfaction.

under investigation can be recognized. Furthermore, customer requirements should be transformed to the design parameters during the third stage which is the analyze phase. This phase also involves developing different alternatives for the design concept and selecting the most appropriate one. While, the fourth stage is the design phase that demonstrates a detailed design for the design concept selected during the previous stage. The verify phase is the last one that assures the validity of the proposed or modified design. This phase entails building prototypes and performing pilot runs to ensure that the desired requirements have been satisfactorily achieved.

Several tools have been proposed in the literature to be exploited in each phase of the DMADV implementation. However, there is no consensus about which tools are the most appropriate to achieve the targets of each phase, even the selection of a specific methodology in the DFSS implementation is still controversial. Therefore, it is recommended by Gregory and Camille [6] that the DFSS users should customize the approach in order to fit their particular applications.

APPLICATION OF THE DMADV METHODOLOGY

Contacting custom-made exhaust tube workshops reveals that the ordered tubes from the tube cutting supplier have some problems. These problems cause additional work on the tubes and poor quality of the manufactured exhaust tube. In addition, ordering customized tube lengths is associated with a higher cost that results in cost ineffective production. Therefore, the tube cutting process at the supplier has been considered for investigation. The supplier current practice in tube cutting is using manual feed tube cutting machines that rely on a stopping guide for adjusting the desired length to be cut from the whole tube.

The Define Phase

Investigating the process of exhaust tube production during the define stage reveals several defects that adversely affect the production. Site visits to the exhaust tube supplier have been conducted to investigate problems in the tube cutting process and to determine the sources of defects. During the site visits, the process has been observed and feedback from engineers and workers at the site have been considered to identify the main problems that are most likely to happen during the process and their main causes. A sample of the interactive questionnaire that has been used for this purpose includes: What are the defect types in your production? What is the frequency of occurrence for each defect type? How do you know about the defects? Is it through inspection or from customer complains? What are the associated maintenance problems in your process? What about the shutdown times to replace parts in the machine? Are you capable of providing your customer with customized lengths? Is it easy to adjust your machine to supply the customer with small amounts of customized lengths? In addition, the economics of the process have been discussed with the engineers.

After the site visit meetings, it has been concluded that the tube cutting process may encounter different problems; some of them are in the form of defects in the cutted tube, while the others are classified as bad effects on the cutting machine itself. To understand the process more thoroughly and to identify the cause and effect relations among the process aspects, the interrelationship diagram [22] for the current tube cutting process has been constructed as shown in Fig. 2. The interrelationship diagram is an effective analysis tool that helps in distinguishing between concerns that serve as causes and those that are consequences. In the interrelationship diagram, the digits recorded below each concern represent the number of in/out arrows. Referring to Fig. 2, the blocks with relatively high number of arrows entering and a low number of arrows leaving represents the consequences or effects. Conversely, the blocks with a relatively high number of arrows leaving and low number of arrows entering represents the causes. Also, tracking back the arrows entering to the causes can be helpful in recognizing the root causes. Different consequences in the form of defects have recognized and coded as follows:

D1: Tube length is shorter than specified.
D2: Tube length is longer than specified.
D3: Deformation of the cross-section's circular shape of the cutted tube.
D4: Irregular tube edges.
D5: Tube bending. (This problem is rare in this case study, but it may be a major problem in other applications).

As mentioned earlier, the consequences are not only limited to effects on the product, but also bad effects on the machine itself may be encountered. These bad effects subsequently affect the quality of the product as well as the machine life. These effects are summarized and coded as follows:

E1: Wear in clamping parts.
E2: Shape deformation of the stopping guide.
E3: Deterioration of the cutting tool that arises from the tube deformation.
E4: Bent in the cutter axis due to the unexpected pressure resulted from the deformed tube.

In this application, the most critical defect arises when the cutted tube length is being shorter than the specified as it ends with a scrapped tube. This problem can be considered as an effective and serious in increasing the cost because of the expensive material of the exhaust tubes which are fabricated from ferrite stainless steel (with 15% Carbon) of high heat resistant. Analyzing the process reveals that relying on the stopping guide that uses the impact technique to assure the

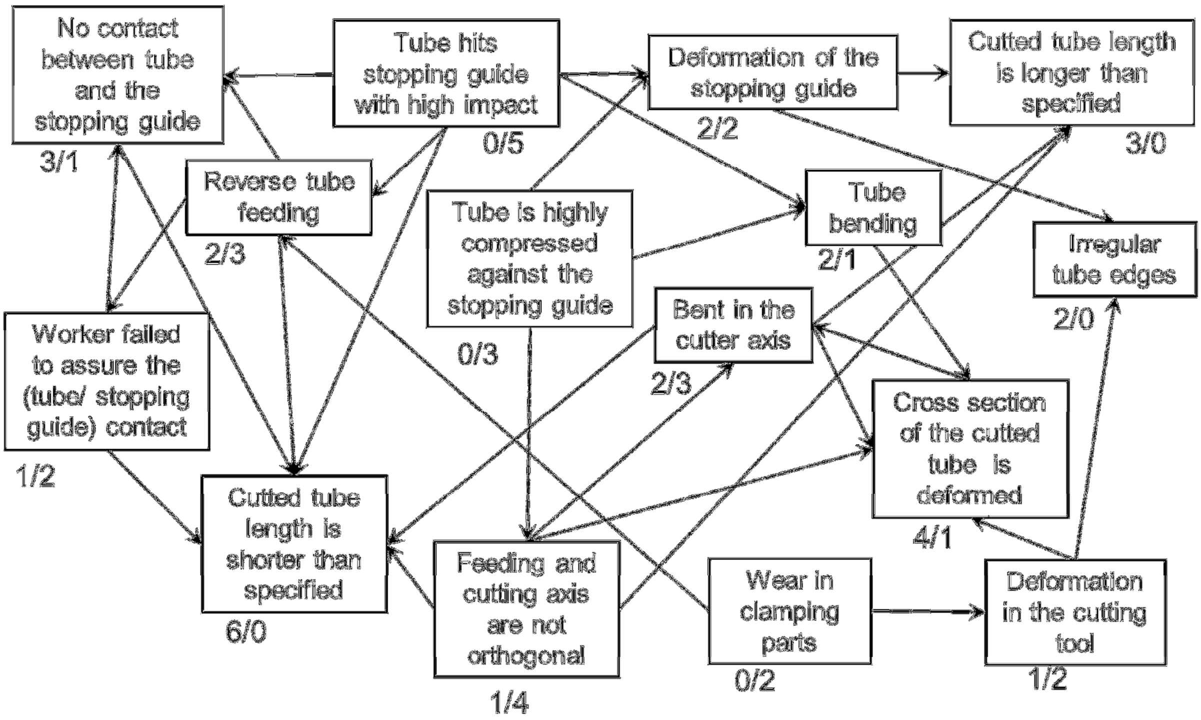


Fig. 2. Interrelationship diagram for the current tube cutting process.

correctness of the specified tube length is considered to be the root cause of the problems. In addition to the analyzed problems, producing customized lengths necessitates timely and costly adjustments of the machine. Besides, in cutting long lengths, the worker needs to check that the tube reaches the stopping guide. This may need another worker to check it, or walking to the other end which consumes more time.

The Measure Phase

The define phase reveals that there is an opportunity to enhance the current process performance by proposing a modified design for the tube cutting machine. Accordingly, the Quality Function Deployment (QFD) is adopted to identify the main attributes of the design improvement process. More details about the QFD methodology and its applications are discussed in [1, 23-25]. In order to implement QFD analysis, a set of data is required that contains the customer needs and the benchmarking data. Consequently, the current measure phase is dedicated to collect the data needed for the QFD. Since the QFD is being used in this research to assist in developing a machine not a product, the customer requirements would not be limited to the exhaust tube manufacturers only because their requirements will be focused only on the attributes of tubes shipped to them. However; the process owner, the machine operator, as well as the maintenance staff, will also have their own requirements.

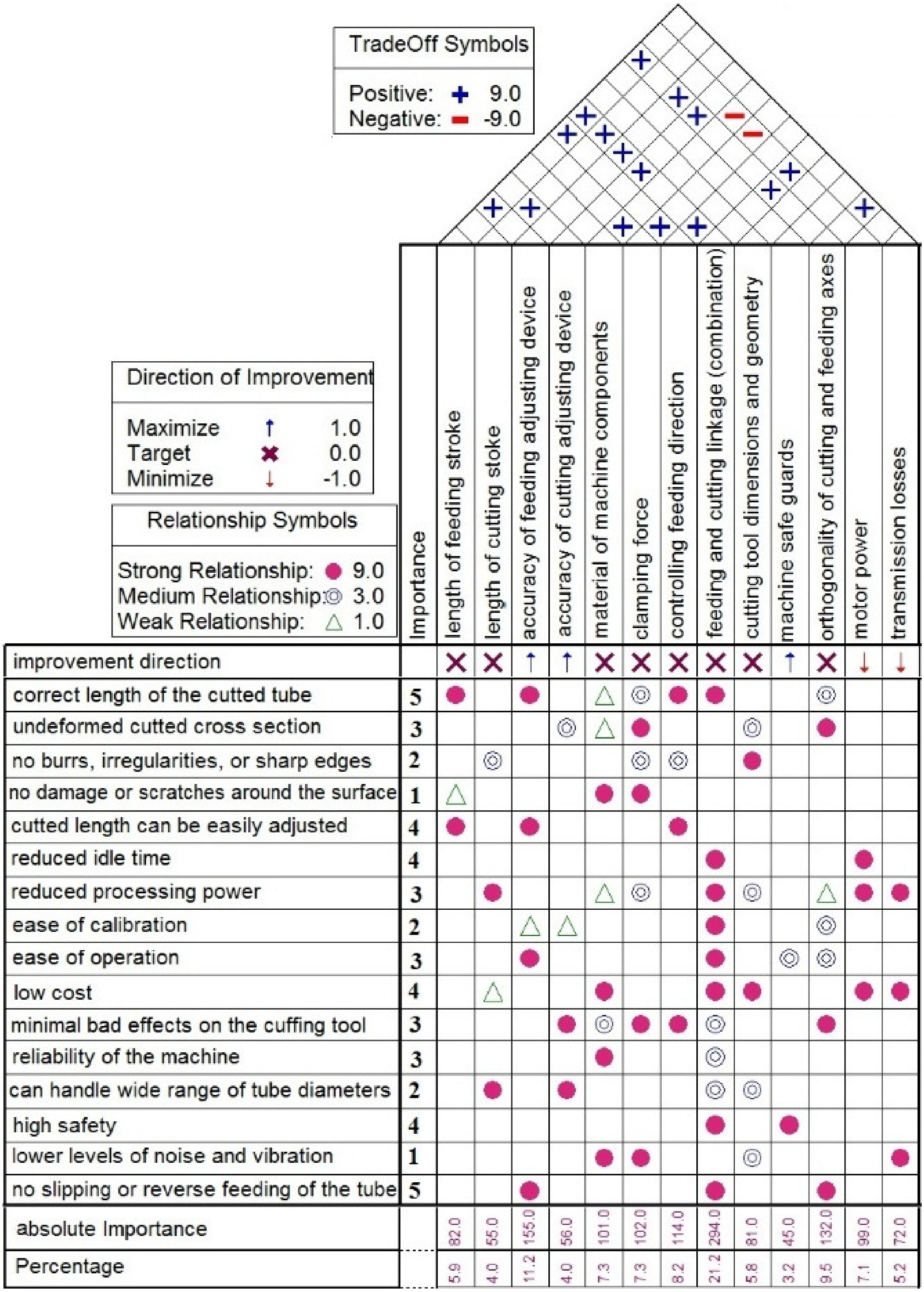
Contacting all the interested parties and performing brain storming sessions, the customer requirements/needs have been identified. Those needs are: correct length of the cutted tube; undeformed cutted cross section; no burrs, irregularities, or sharp edges; no damage or scratches around the surface; the cutted length can be easily adjusted; reduced idle time; reduced processing power; ease of calibration; ease of operation; low operation cost; minimal bad effects on the cutting tool; high reliability; handling wide range of tube diameters; high safety; lower levels of noise and vibration; as well as no slipping or reverse feeding of the tube.

The Analyze Phase

After the identification of the customer needs, the House of Quality (HoQ) has been constructed with the customer requirements located in the left portion of the house and have been assigned scores ranges from 1 to 5 according to their relative importance (the higher is the more important) as shown in **Fig. 3**. In this phase, the HoQ is employed to convert the customer requirements (WHATs) into technical characteristics (HOWs). Accordingly, a set of technical characteristics have identified to translate the voice of customers to engineering requirements in order to assure developing the machine that satisfies the customer requirements. The considered technical characteristics are located in the upper portion of the HoQ. Those characteristics can be listed as: length of feeding stroke, length of cutting stroke, accuracy of feeding adjusting device, accuracy of cutting adjusting device, material of machine components, clamping force, controlling feeding direction, feeding and cutting linkage (combination), cutting tool dimensions and geometry, machine safeguards, orthogonality of cutting and feeding axes, motor power, and transmission losses. The direction of improvement for each technical characteristic is indicated below each one.

The strength of the relationship between each customer requirement and each technical characteristic is symbolically represented in a matrix located in the core of the HoQ. The roof of the house illustrates the correlation between the technical characteristics. In the bottom of the house, the importance ratings are provided. These give an insight of the importance of each technical characteristic's contribution in achieving the target of the design. To compute these ratings for each technical characteristic, the numerical values of the symbols that have been assigned in its column in the relationship matrix are multiplied by the corresponding customer importance ratings and then adding the results.

Besides, performing Pareto analysis can help in highlighting the vital few characteristics. A Pareto chart has been constructed, as shown in Fig. 4, to rank the technical characteristics from the largest to the smallest according to their percent importance in realizing the design targets and to judge their cumulative contribution as well. Examining the chart reveals that approximately 50% of the contributions in achieving customer requirements are attributed to four technical characteristics. These are feeding and cutting linkage (combination), the accuracy of cutting adjusting device, orthogonality of cutting and feeding axes, and controlling feeding direction. Focusing on these characteristics is critical to achieve the proposed design targets. Accordingly, brainstorming sessions, reviewing literature, and patent searching have been utilized during concept generation. As a result, several ideas have been proposed and discussed to combine the feeding and cutting motions in order to error proof the process, avoid reverse feeding, and reduce the idle time as well. After analyzing the different generated ideas, the concept selection and enhancement have been accomplished. This step of the DFSS implementation has resulted in a conceptual design for a combined tube feeding and cutting mechanism.



	Importance	length of feeding stroke	length of cutting stoke	accuracy of feeding adjusting device	accuracy of cutting adjusting device	material of machine components	clamping force	controlling feeding direction	feeding and cutting linkage (combination)	cutting tool dimensions and geometry	machine safe guards	orthogonality of cutting and feeding axes	motor power	transmission losses
improvement direction		✖	✖	↑	↑	✖	✖	✖	✖	✖	↑	✖	↓	↓
correct length of the cutted tube	5	●		●		△	◎	●	●			◎		
undeformed cutted cross section	3				◎	△	●			◎		●		
no burrs, irregularities, or sharp edges	2		◎				◎	◎		●				
no damage or scratches around the surface	1	△				●	●							
cutted length can be easily adjusted	4	●		●				●						
reduced idle time	4								●				●	
reduced processing power	3		●			△	◎		●	◎		△	●	●
ease of calibration	2			△	△				●			◎		
ease of operation	3			●					●		◎	◎		
low cost	4		△			●			●	●			●	●
minimal bad effects on the cuffing tool	3				●	◎	●	●	◎			●		
reliability of the machine	3					●			◎					
can handle wide range of tube diameters	2		●		●				◎	◎				
high safety	4								●		●			
lower levels of noise and vibration	1					●	●			◎				●
no slipping or reverse feeding of the tube	5			●					●			●		
absolute Importance		82.0	55.0	155.0	56.0	101.0	102.0	114.0	294.0	81.0	45.0	132.0	99.0	72.0
Percentage		5.9	4.0	11.2	4.0	7.3	7.3	8.2	21.2	5.8	3.2	9.5	7.1	5.2

Fig. 3. House of quality for the proposed tube cutting machine.

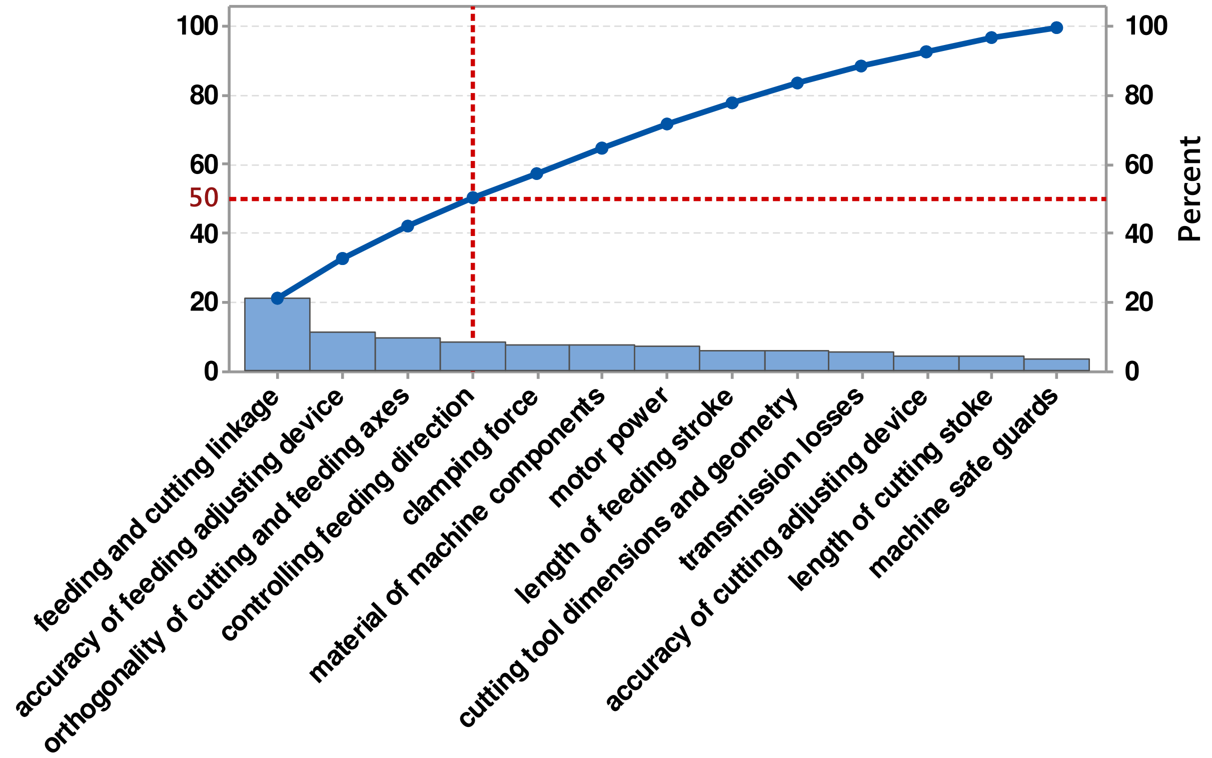


Fig. 4. Pareto chart (percentage contribution of different technical characteristic).

The Design Phase

A conceptual design of a compound mechanism is proposed for achieving an acceptable level of customer requirements as discussed in the previous analyze phase. This mechanism must have the capability of providing feeding motion of tube associated with cutting motion in order to overcome the most of the drawbacks in the current practice.

Some of the published works in the literature are dealing with designing tube cutting machines. Manual cutting of thin tubes is discussed in [26] using the sharp hardened cutting wheels as manual tools. Moreover, the problems such as; an unacceptable level of material waste, low production efficiency and the difficulties of clamping, in addition to large size deviation in the cutting process are discussed in [27]. Some of these problems can be treated via planetary cutting technique with the usage of two symmetrical sharp cutting wheels. Furthermore, multi-way power hacksaw arrangement as cutting bars machine is introduced in [28] to reduce the human effort during repeatable bar cutting processes. Besides, different designs of continuous pipe cutting machine using sensors are presented in [29]. Moreover, a prototype of automatic pipe cutting machine for small scale industries is presented in [30]. Additionally, automotive manifolds exhaust systems fabricated from ferrite stainless steel of high heat resistant is presented in [31].

Compound mechanism preliminary layout

A preliminary layout of the suggested compound mechanism for the developed tube cutting machine is shown in Fig. 5. This compound mechanism can be used for providing both feeding and cutting motions. The arrangement of this suggested

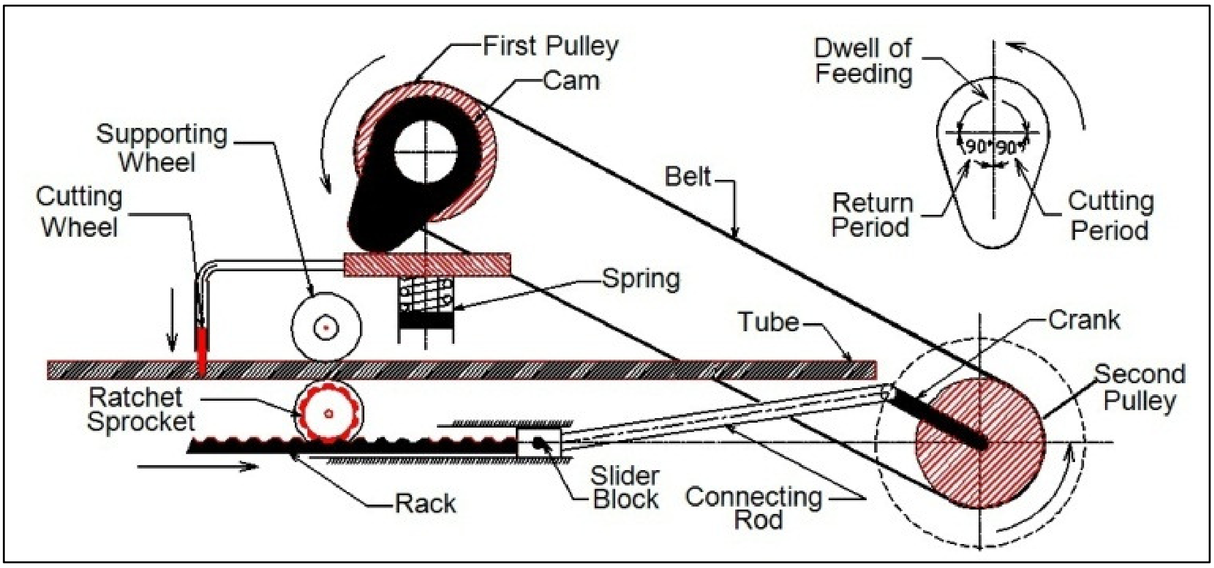


Fig. 5. Preliminary layout of compound mechanism.

compound mechanism consists of a slider-crank mechanism, two identical pulleys, timing belt, a cam and its follower carrying cutting wheel, a ratchet wheel connected with a reciprocating rack, in addition to guides and supporting wheels. These supporting wheels have diameters that equal to ratchet pitch diameter. The accurate adjustable strokes of the crank-rocker mechanism can control the desired predefined lengths of tubes. Where, the feeding of each tube's portion to be cut equals to the selected accurate stroke of the crank-rocker mechanism. Furthermore, the cam and its follower, in addition to a retained helical spring afford an effective control of the cutting process.

The crank rotates at the same axis of the second pulley; hence the crank rotation motion is accompanied with timing belt motion which is rotating via the first pulley for giving a rotating motion to the cam's axis. The cam profile consists of three portions. The first one corresponds to 90^0 of cam's cycle which is responsible for giving the downward cutting motion, while the second one is responsible for giving the upward return motion to the cutting wheel through 90^0 of cam's cycle. Finally, the third one is called the dwell portion which corresponds to 180^0 of cam's cycle. This portion is responsible for keeping the cam's follower in its place without motion for affording a chance to the slider-crank mechanism in addition to the control ratchet wheel to drag the tube through the requested feeding motion. The feeding motion depends on the ratchet wheel which has an active work in a certain direction and it has non-active work in the other direction as introduced in [32]. These ratchet wheels (sprockets) are similar to the types which are used in the air bicycles. These ratchet wheels have an active rotatory motion that rotates its shaft through a certain rotation's direction. Besides, these wheels are freely rotating without driving its shaft's axis in the opposite rotation's direction. Hence, the rack which is connected with the sliding block of the slider-crank mechanism can rotate the ratchet wheel via its active direction of rotation through 180^0 of the cam's cycle for dragging the tube in feeding direction with exact feeding length. This feeding length equals to the double of the crank length (mechanism's stroke).

A detailed 3D CAD model of the compound mechanism

A comprehensive three dimensional model of the suggested tube cutting machine's design and simulation containing the compound mechanism's details has been created using 3D CAD Solidworks Software [33]. The developed tube cutting machine containing this compound mechanism's details is shown in Fig. 6 and Fig. 7. The frontal elements of developed tube cutting machine containing the compound mechanism elements are shown in Fig. 6, while Fig. 7 shows these elements of tube cutting machine from the other side.

The Verify Phase

A prototype, which is shown in Fig. 8, has been manufactured to test the validity of the suggested design. The cam and the slider-crank mechanisms' elements are fabricated from a suitable material as Acetal. The Acetal is a light and easily machined material which has an approximately tensile strength equals (61 MPa) and shear strength equals to (55 Mpa). The tube cutting machine elements are installed on a wooden table.

The present prototype indicates that the suggested system, which designed for giving simultaneous tube feeding and cutting motion, is valid for using it as tube cutting machine which has the ability of controlling and combining both of the feeding and cutting motions. Where, the requested feeding motion of each tube's portion can be directly achieved via selecting the exact desired stroke of the crank-rocker mechanism. Moreover, the cam mechanism and the retained helical spring afford an accurate control of the cutting process.

The suggested machine arrangement affords an easy way for the machine operator to select the exact desired cutting lengths, where the feeding of the desired cutted length equals to double of the adjustable crank length of mechanism. Combining the feeding and cutting mechanisms is the most important benefit of the suggested machine, which assures cutting the desired accurate lengths of exhaust tubes, especially they are fabricated from an expensive material. Also, driving both feeding and cutting mechanisms via the same driving shaft assures achieving an accurate timing control between feeding and cutting processes. On the other hand, the current machines commonly use the manual clamping and feeding processes before starting the cutting process which mostly leads to cut short lengths. Besides, the process of adjusting the manual feeding increases the idle time which decreases the productivity. However, the suggested machine saves the idle time during cutting of similar repeated processes. Once the operator of the suggested machine adjusts the crank length according to the desired cutting length, he can operate the machine to cut the first exhaust tube which can be measured for approving the correct cutting requirements. Then, the machine can work continuously with very low idle time in addition to elimination of possibilities of wrong cutting.

The suggested machine arrangement affords the needed time to the cutting tool for doing the requested cutting process during the completely stopping period of the feeding mechanism in order to avoid any deterioration or irregular cut. Furthermore, clearance of moving mechanical parts as bearings can affect the cutting lengths accuracy with a tolerance less than ±2mm. Fortunately, this problem can be treated via a suitable calibration during selecting the length of the adjustable crank.

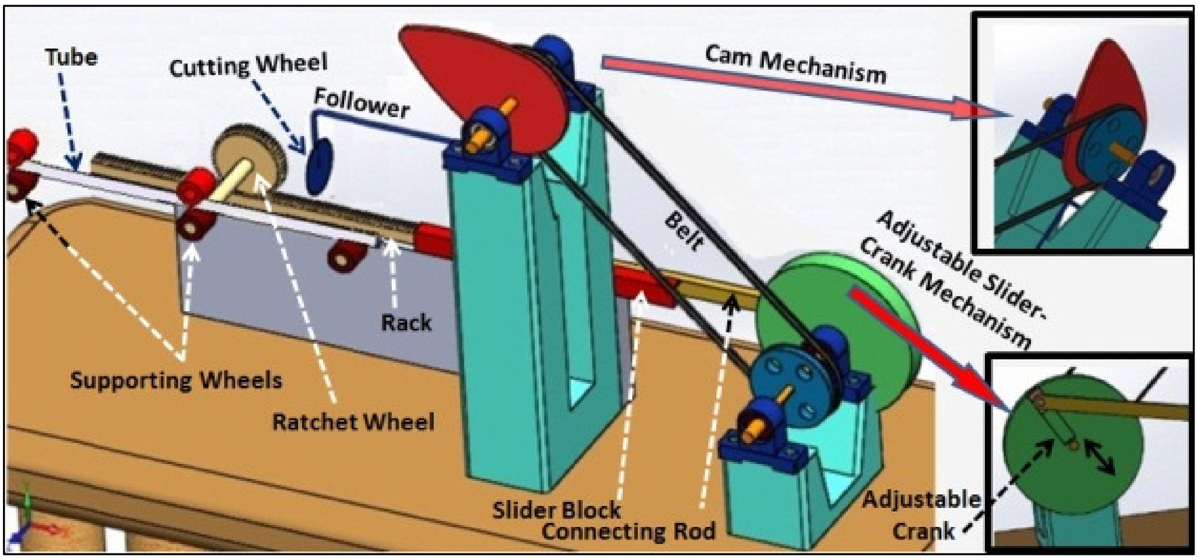


Fig. 6. Frontal elements of developed tube cutting machine.

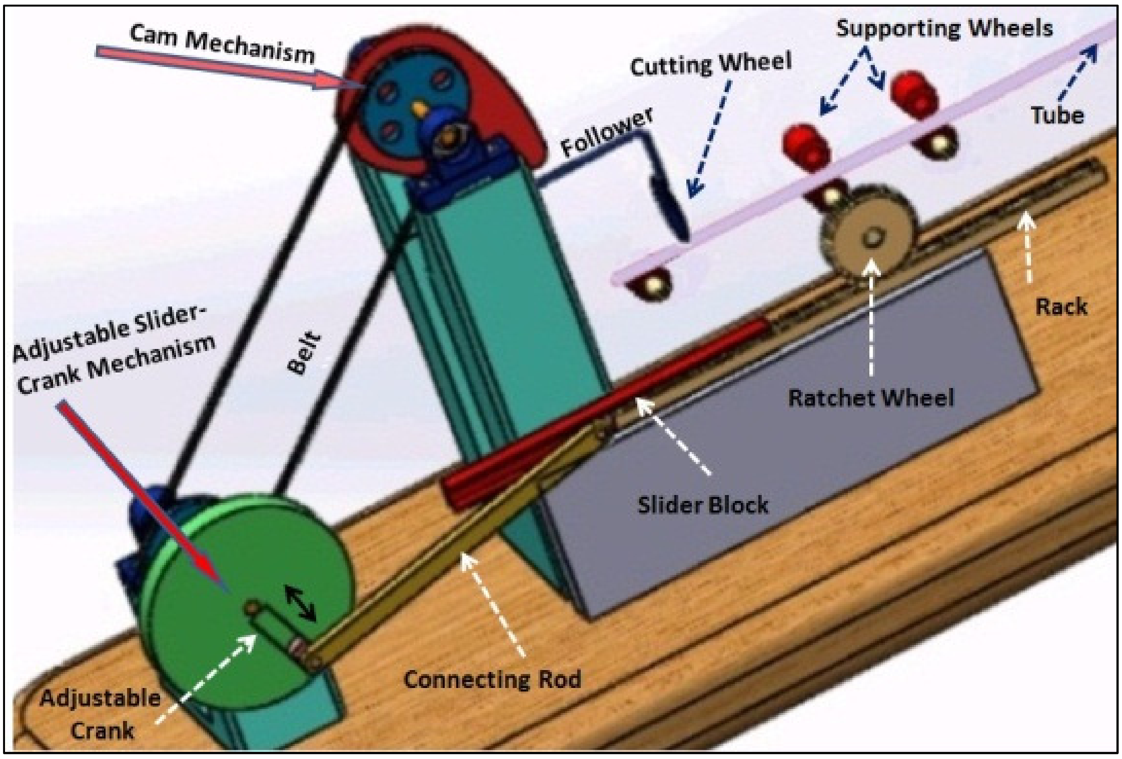


Fig. 7. Other elements of developed tube cutting machine.

The prototype of the suggested machine has been operated many times for checking the validation of the proposed design. A simple arrangement was used instead of actual cutting tool for adding small scratch to the examined tube. The distance between two successive scratches gives the length of feeding which is the desired length of cutted tube. This distance compared many times with the desired cutting tube length. The errors were acceptable and less than 4 mm which can be treated through assembling the exhaust tubes. The validity testing of the suggested machine prototype using pilot runs reveal that the developed mechanism performs its intended

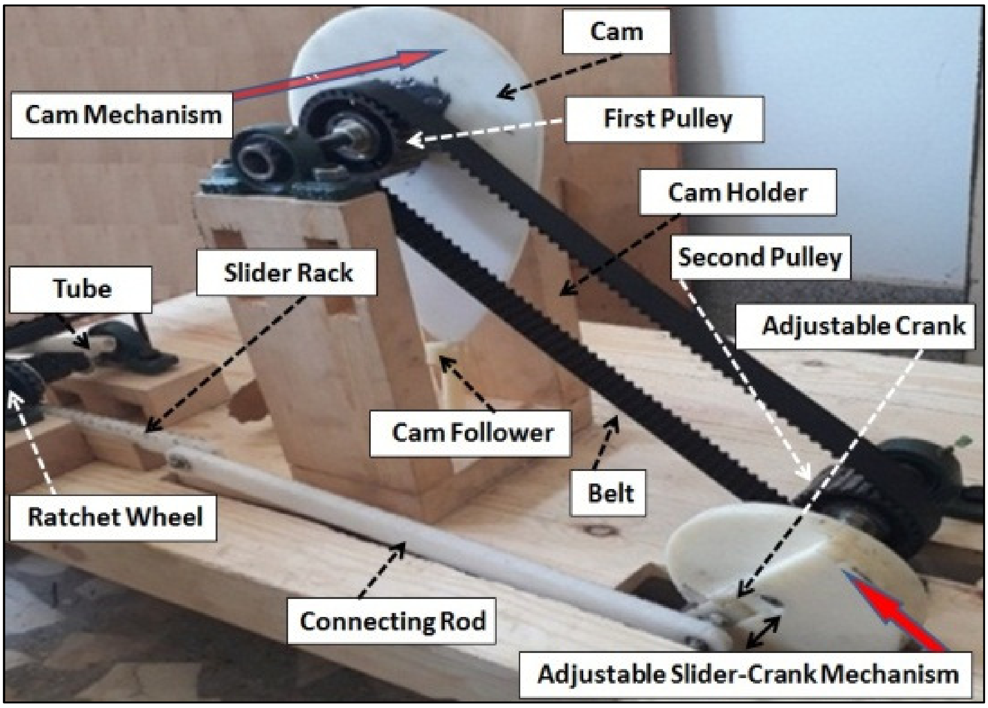


Fig. 8. Prototype of developed tube cutting machine.

task adequately. Additionally, this developed mechanism decreases the chances of cutting wrong tube lengths.

CONCLUSION

In this paper, a combined mechanism for simultaneous tube feeding and cutting has been developed based on the application of Design for Six Sigma. This has been achieved in response of complaints and drawbacks in the current practice of tube cutting process. A case study involving cutting tubes to predefined length to be supplied to custom-made exhaust tube manufactures has been considered and the DMADV methodology has been employed. Several tools have been incorporated during the different phases of the DMADV implementation as needed. The methodology inherits a great flexibility so that it can be customized to fit the targeted application scenario.

The suggested compound mechanism consists of planar four bar slider-crank mechanism and cam mechanism, in addition to mechanical control elements such as; ratchet sprockets, cam follower and guides. The predefined lengths of tubes can be adjusted by selecting the different exact desired strokes of crank-rocker mechanism. Hence, the suggested machine can afford a wide range of cutting tube lengths. Moreover, the cam mechanism affords an accurate control of the cutting process. A detailed 3D CAD model has been built using Solidworks Software. In addition to a prototype that has been manufactured to test the validity of the proposed design as a proof of concept. Pilot runs of the prototype demonstrate the capability of the mechanism to adequately perform the feeding and cutting with chances of errors eliminated. Also, the developed design successfully prevented the reverse feeding, decreased the machine idle time, and significantly reduced the human interaction without using costly automation and controls.

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